Comparison of Outcomes for Off-Pump Versus On-Pump Coronary Artery Bypass Grafting in Low-Volume and High-Volume Centers and by Low-Volume and High-Volume Surgeons

Benedetto U, Lau C, Caputo M, Kim L, Feldman DN, Ohmes LB, Di Franco A, Soletti G, Angelini GD, Girardi LN, Gaudino M.

[2]Bristol Heart Institute, University of Bristol, School of Clinical Sciences, Bristol, UK

[1]Weill Cornell Medical College, Department of Cardiothoracic Surgery, New York City, NY, United States

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Corresponding Author
Umberto Benedetto MD PhD
Bristol Heart Institute, Bristol Royal Infirmary,
Tyndall Avenue,
BS8 1TH, Bristol, United Kingdom
Tel: +44 (0)117 928 9000
Email: Umberto.benedetto@bristol.ac.uk

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Abstract

Background: Few centres and cardiac surgeons in the U.S. perform enough off-pump coronary artery bypass (OPCAB) procedures to be considered ‘‘specialists’’. The clinical implications of this observation remain unclear. We investigated whether the volume of OPCAB procedures by hospital and individual surgeon influenced patient outcomes when compared with on pump coronary artery bypass (ONCAB) surgery.

Methods: A total of 546,243 OPCAB (26.1%) and 1,547,851 ONCAB (73.9%) procedures performed from 2003 to 2011 and collected in the US Nationwide Inpatient Sample were included in the analysis. Hierarchical logistic regression models were used to compared OPCAB and ONCAB in the whole population and across OPCAB volume quartile groups to investigate the effect of hospital and surgeon procedures volume on early in hospital mortality.

Results: In patients requiring 2 or more grafts**,** OPCAB compared with ONCAB was associated with increased risk-adjusted mortality when performed in low volume centres (<29 cases/year) (OR; 1.32;95%CI 1.06-1.57) or by low volume surgeons (<19 cases/year) (OR 1.26; 95%CI 1.02- 1.56). In high OPCAB volume centres (≥164cases/year) and surgeons (≥48 cases/year), OPCAB reduced mortality compared with ONCAB in cases requiring a single graft (OR 0.66; 95%CI 0.49-0.89 and OR 0.33; 95%CI 0.22-0.47) or 2 or more grafts (OR 0.82; 9%%CI0.66- 0.99 and OR 0.63; 95%CI 0.49- 0.81).

Conclusions: OPCAB surgery in high volume hospitals and surgeons reduces mortality compared to ONCAB surgery. OPCAB surgery by low volume centres and surgeons should be discouraged.

Introduction

Controversy still remains whether on off-pump coronary artery bypass (OPCAB) grafting is superior to on-pump coronary artery bypass (ONCAB) surgery in terms of in-hospital outcomes [1-2]. Although several large clinical trials [3-5] and institutional reports have attempted to compare the safety and efficacy of both approaches [6-7], reported outcomes remain mixed [8]. Volume–outcome relationships within surgical practice results are well known [9-11]. Studies investigating volume at individual surgeon or hospital level are attractive to physicians and administrators because they allow for an intuitive measure of ‘‘expertise’’ and a proxy of enhanced safety and quality. It has been suggested that programs with greater OPCAB experience may have better results than those that perform these procedures less frequently [12-13] but sparse and conflicting results have been reported [14-16]. A recent report from the Society of Thoracic Surgeons (STS), showed that only a few cardiac surgeons and centres in the U.S. perform enough OPCAB procedures to be considered ‘‘specialists’’ [17]. However, the clinical implications of this observation remain unknown with some author advocating that OPCAB should be abandoned [8]. We investigated wheatear OPCAB hospital and surgeon volume significantly influenced early in hospital mortality when compared with ONCAB in a large U.S. cohort.

Methods

Data sources

Patient discharge records reported for in-hospital admissions from 2003 to 2011 included in the Nationwide Inpatient Sample (NIS) databases were evaluated. The NIS represents a 20% stratified random sample of all hospital discharges in the United States, and collection, validation, and maintenance of the datasets are performed by the Agency for Healthcare Research and Quality [18]. The NIS datasets represent the largest publicly available inpatient care databases within the United States. Each year the NIS captures patient discharges reported from approximately 1000 American Hospital Association centres. The NIS data use national hospital survey strata to weight each of the participating hospitals. Weights are provided for each discharge record, allowing nationally representative study populations to be produced. Weill Cornell Medical College confirmed that institutional review board approval and informed consent were not required for this study because it uses a unidentified administrative database.

Patients

The study included discharge records from 999 hospital and 44 states in NIS datasets from 2000 to 2010 that specifically reported unique hospital identifiers for the study time period with selected International Classification of Diseases, 9th Revision, Clinical Modification (ICD-9-CM) procedure and diagnostic codes. Discharge records for patients undergoing CABG procedures were identified using the following ICD-9-CM procedure codes: 30.10, 36.11, 36.12, 36.13, 36.14, 36.15, or 36.16. The concomitant use of cardiopulmonary bypass (CPB) support was identified by records that also included the following ICD-9-CM procedure codes for bypass support: 39.61 or 39.66. Discharge records for patients with concomitant cardiac valve procedures (ICD-9-CM codes 35.20, 35.21, 35.22, 35.23, 35.24, 35.25, 35.26, 35.27, 35.28, 35.11, 35.12, 35.13, 35.14) or other cardiotomy (ICD-9-CM code 37.11) for purposes other than CPB were excluded. Patient-level and hospital-level variables were included as baseline characteristics. The Agency for Healthcare Research and Quality's comorbidity measures based on the Elixhauser method were used to identify comorbid conditions [19]. Hospital-level data elements were derived from the AHA Annual Survey Database.

Outcomes measured

The primary outcome was in-hospital all-cause mortality for the overall cohort of isolated CABG. Secondary outcome measures were length of stay and total costs.

Statistical analysis

Patients were stratified into OPCAB and ONCAB cohorts for descriptive purposes. OPCAB hospital volume was determined by calculating the total number of isolated operations performed for each centre during the study period (2003-2011). OPCAB hospital volume was categorized into quartiles: low (<25th percentile), medium (25–49th percentile), high (50–74th percentile), and very high (≥75th percentile). OPCAB and ONCAB were compared in the whole population and across OPCAB hospital volume and surgeon quartile groups. Weighted values of patient-level observations were generated to produce a nationally representative estimate of the entire US population of hospitalized patients. Differences between categorical variables were tested using the Pearson's chi-square test (Rao & Scott adjustment), and differences between continuous variables were tested using the Student t test. P Value <0.05 was considered significant. Two separate hierarchical regression models with the unique hospital identification number incorporated as random effects within the model were used [20]: model 1: clustering for centres + patient level variables including age, gender, race, elective admission and risk related to coexisting medical conditions + hospital-level variables such as hospital region, location teaching status, and bed size; model 2: model 1+ ONCAB hospital volume and year of surgery. The last two variables were forced into the model to correct final estimates for the influence of operative volume during ONCAB [9] and to account for potential variation in the quality of care during the study period [21]. Hierarchical mixed-effects logistic regression models were used for categorical dependent variables such as primary and secondary outcomes, and hierarchical mixed-effects linear regression models were used for continuous dependent variables such as cost of care and length of stay. Subgroup analysis on hospital mortality according to the number of grafts performed (1 versus ≥2 grafts) across hospital and surgeon volume quartiles was performed. The analysis was repeated according to individual surgeon OPCAB volume including cases that specifically reported unique physician identifiers for the study time period. Categorical variables are expressed as a percentage of the group of origin. Continuous variables are reported as mean ± standard error. Odds ratios (OR) with a 95% confidence interval (CI) are used to report the results of logistic regression models. Reported probability values are 2-tailed and were considered statistically significant if <0.05. Data analyses were performed using R version 3.1.2 and survey package (T. Lumley 2014 "survey: analysis of complex survey samples". R package version 3.30).

Results

OPCAB Hospital Volume analysis

The study population consisted of 2,094,094 patients who underwent isolated CABG during the period 2003-2011 in 999 US centres. OPCAB and ONCAB procedures were performed in 546,243 (26.1%) and 1,547,851 (73.9%) cases respectively (Figure 1). OPCAB hospital relative volume and hospital rate were extremely heterogeneous across the centres (Figure 2). Median OPCAB and ONCAB hospital volume per year was 82 (IQR: 29-164) and 308 (IQR 145-569) procedures respectively. Patient-level and Hospital level variables distribution in the OPCAB and ONCAB groups is reported in Table 1. Overall, differences between the two groups were not clinically relevant and operated on both directions. The number of procedures involving a single graft only, were higher in the OPCAB group. An overview on unadjusted outcomes is summarized in Table 2. Table 3 shows risk-adjusted effect of OPCAB versus ONCAB on outcomes investigated across OPCAB hospital volume quartile. In centres performed less than 29 cases per year, OPCAB was associated with a significantly higher risk-adjusted mortality, length of stay and overall costs. On the other hand, in centres performing ≥164 cases per year, OPCAB was associated with a significant 20% relative risk reduction in mortality compared to ONCAB.

OPCAB Surgeon Volume analysis

The unique physician identifiers were available only from 2003 to 2009 including a total of 1,024,872 cases performed by 6,724 surgeons. OPCAB and ONCAB were performed in 295,045 (28.8%) and 729,827 (71.2%) cases respectively. Median OPCAB and ONCAB surgeon volume per year was 19 (IQR 6-48) and 79 (IQR 30-153) procedures respectively. Risk-adjusted estimates showed that surgeons performing less than 48 OPCAB cases per years, had a higher risk adjusted hospital mortality, prolonged length of stay and total costs compared to ONCAB surgery. On the other hand, for surgeon performing ≥48 OPCAB cases per year, OPCAB was associated with a significant 42% relative risk reduction in mortality and significantly reduced overall costs when compared with ONCAB surgery.

Subgroup analysis according to number of grafts performed.

In case requiring a single graft only, OPCAB compared with ONCAB did not increase mortality in low volume hospitals and surgeons. In high OPCAB volume hospitals and surgeons, single graft OPCAB was associated with a lower adjusted-risk mortality when compared to ONCAB (Table 5).

Discussion

Despite the initial enthusiasm regarding the potential benefit from OPCAB over ONCAB in improving hospital mortality [6,7], several randomized trials have failed to demonstrate its superiority [3-5] and others have reported poorer outcomes [3]. These trials have been criticized by those who believe that OPCAB increased technical complexity, hospital volume and surgeon experience plays a major role in determining outcomes [12,13]. In the ROOBY trial [3], participating surgeons were required to have previously performed 20 OPCAB procedures a lack of experience which could explain the worse composite outcomes at1 year in this group of patients. In the more recent CORONARY trial [4], surgeons were required to have performed more than 100 procedures in OPCAB and ONCAB., Patients undergoing

OPCAB required less transfusion, reoperation for perioperative bleeding, respiratory complications, and acute kidney injury than those undergoing ONCAB. In the GOPCABE study [5], where surgeons were required to be established experts in the performance of OPCAB with and an average of 514 procedures (median, 322) no significant differences between OPCAB and ONCAB were found. It should be noted that none of these trials had sufficient power to accurately assess clinically important differences in mortality. In fact, to provide a power of 80% to detect a 30% relative risk reduction in the rate of in-hospital mortality or stroke (~2%), the required total sample size would be 19,506. The CORONARY, GOPCABE and ROOBY trials have randomly assigned 4,752, 2,539 and 2,203 patients respectively and therefore, they were largely underpowered to detect differences in mortality or stroke. Expertise in OPCAB by individual surgeon and hospital seems therefore, to be an important determinant of outcome.[17,22]. However, little has been previously published, and s with conflicting results reported [12-16].

Large registries have the potential to overcome the limitation of underpowered randomized controlled trials in detecting differences in hard clinical end points such as mortality. The present risk-adjusted analysis on US Nationwide Inpatient Sample on a very large number of procedures provides important insight into the relative impact of OPCAB hospital and surgeon volume on outcomes. We found that OPCAB when performed in low volume centres and by low volume surgeons, was associated with significantly increased risk-adjusted mortality length of stay and overall costs compared with ONCAB surgery. On the contrary, OPCAB was associated with a lower risk adjusted mortality when performed in high volume hospital (≥164 cases/year) and surgeons (≥48 cases/year). Subgroup analysis according to number of grafts performed suggested that single graft OPCAB is as safe as ONCAB even in low volume hospitals and surgeons. On the other hand single graft OPCAB in high volume hospitals and surgeons was associated with a lower risk-adjusted mortality when compared to single ONCAB graft.

It could be argued that patient selection bias not accounted by the present risk-adjusted model, might partially explain the increased mortality after OPCAB in case of low-volume (only high risk patients received OPCAB). However, the fact that, in low volume centres, single graft but not multiple graft OPCAB was as safe as ONCAB supports the hypothesis that the increased technical complexity particularly relevant in case of multiple OPCAB grafts has the potential to increase mortality and morbidity in a low volume setting [3]. Nevertheless, this result suggests that "sporadic" OPCAB practise is unlikely to neutralize the excess of mortality compared to ONCAB in selected cases and therefore, this strategy seems questionable. The reduced risk-adjusted mortality in patients undergoing OPCAB in a high volume hospital, ≥164 cases/year) provides evidence of its potential superiority over ONCAB. Moreover, the comparable sample size of the two groups (Table 3) in high OPCAB hospital volume setting underlies a neutral patient selection process which strength our conclusions.

The association between surgical case volume and outcome after coronary artery bypass graft surgery has been extensively studied and have led to the development of guidelines by the American Heart Association/ American College of Cardiology [23] specifying the minimum number of procedures performed annually by cardiac surgeons. Based on our findings, future guidelines should include OPCAB high volume programs as they have the potential to reduce operative mortality. Low volume OPCAB hospital and surgeon should be discourage from undertaking multiple graft OPCAB surgery.

Study Limitations

This study has select limitations and considerations that deserve further discussion. As previously discussed, the inherent selection bias represented at the surgeon level for the performance of OPCAB versus ONCAB must be considered in any such comparative analysis in particular in a low volume setting. Furthermore, conversion rate from OPCAB to ONCAB is a well-known risk factor for hospital mortality [24] but it is not captured by NIS. However, surgeons with very low case volumes are more likely to convert OPCAB procedures to ONCAB compared to surgeons with high case volumes [24]. Therefore, such an inherent bias is likely to determine an underestimation of the detrimental effect of OPCAB over ONCAB in case of low OPCAB volume. We used in-hospital mortality rate as the primary outcome measure. We were unable to obtain data on out of hospital deaths (eg, 30 days) which would have been preferable. It would also have been desirable to include other risk-adjusted adverse outcome measures such as surgical complications. Although conditions like stroke (ICD-9-CM codes 997.02, 362.31, 368.12, 781.4, 433.11, 435, and 434) and acute renal failure (ICD-9-CM code 584) are reported in the NIS, it is not possible to discriminate if there were present on the admission or if they occurred after surgery and therefore, we decide not to include them in the analysis. Length of stay and total costs are unbiased secondary outcomes anticipated to be associated with postoperative complications rate and their association with the treatment effect across OPCAB volume quartiles supports our conclusion. Finally, the potential for unrecognized miscoding of diagnostic and procedure codes must be recognized in any secondary analysis of administrative data. Nevertheless, in the assessment of hospitals and surgeons volume and their effect on risk-adjusted mortality, the use of NIS provides great strength in its ability to capture a large, broadly generalizable patient population and surgeons with a great range of experience. As a result, these analyses provide important insight into an unanswered question regarding the influence of annual hospital and surgeon OPCAB and ONCAB volume on in hospital mortality, length of stay and costs.

In conclusion, OPCAB surgery in high volume hospitals and surgeons reduces mortality compared to ONCAB surgery. OPCAB surgery by low volume centres and surgeons should be discouraged since it increases mortality when compared with ONCAB surgery. Contrary to recent reports suggesting that OPCAB should be abandoned [3,8], our findings suggest that OPCAB programs should be maintained in selected high volume centres. Furthermore, OPCAB surgery adoption by institutions prepared to develop a proper programme, should be encouraged, given its potential to significantly lower mortality rates when compared with ONCAB surgery.

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Disclosures

None

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Table 1. Descriptive statistics for patients undergoing OPCAB and ONCAB

	OPCAB	ONCAB	P-value
	n=546,243	**n=1,547,851**	
Age (years)	65.4±0.1	65.0±0.1	0.0009
Female	29.5%	26.7%	<0.0001
White	59.2%	61.6%	0.12
Other than white	40.8%	38.4%	
Elective admission	45.2%	46.5%	0.11
Single graft performed	20.6%	12.9%	<0.0001
Coexisting medical conditions			
Acquired immune deficiency syndrome (AIDS)	0.1%	0.1%	0.0004
Alcohol abuse	2.6%	2.4%	0.18
Chronic blood loss anaemia	1.3%	1.4%	0.26
Chronic lung disease	22.4%	21.6%	0.06
Coagulopathy	8.3%	9.9%	<0.0001
Congestive Heart Failure	1.3%	0.8%	<0.0001
Deficiency anaemia	15.8%	15.0%	0.31
Depression	4.8%	4.7%	0.62
Diabetes with chronic complication	5.6%	6.1%	0.03
Drug abuse	1.0%	0.9%	0.04
Fluid and electrolyte disorders	19.8%	18.8%	0.37
Hypertension	69.9%	72.2%	<0.0001
Hypothyroidism	7.3%	7.3%	0.69
Liver disease	1.0%	0.8%	0.0002
Lymphoma	0.3%	0.3%	0.96
Metastatic cancer	0.2%	0.1%	<0.0001
Obesity	13.5%	15.0%	0.01
Other neurological disorders	2.7%	2.6%	0.22
Paralysis	1.1%	1.1%	0.64
Peptic ulcer disease excluding bleeding	0.3%	0.3%	0.92
Peripheral vascular disease	13.7%	12.7%	0.02
Psychosis	1.3%	1.3%	0.45
Pulmonary circulation disorders	0.1%	0.1%	0.21
Renal failure	10.0%	9.1%	0.001
Rheumatoid arthritis/collagen vascular diseases	1.5%	1.5%	0.56
Solid tumour without metastasis	1.1%	1.0%	0.01
Uncomplicated Diabetes	29.3%	32.1%	<0.0001
Valvular disease	0.4%	0.3%	<0.0001
Weight loss	2.1%	1.7%	0.001
Hospital-level variables			
Location			0.93
Urban	95.7%	95.7%	
Rural	4.3%	4.3%	
Teaching Hospital			
Yes	58.3%	57.5%	0.73
No	41.7%	42.5%	
Hospital bed size			

Small	8.3%	6.5%	0.007
Medium	23.4%	17.3%	
Large	68.3%	76.2%	
Operative Data			
Single graft	20.6%	12.9%	<0.0001
Previous CABG	1.3%	1.3%	0.85

OPCAB: off-pump coronary artery bypass grafting; ONCAB: on-pump coronary artery bypass grafting

Table 2. Crude incidence of outcomes in OPCAB versus ONCAB according to OPCAB hospital volume

		Overall	1st OPCAB HV quartile (<29/yr)	2nd OPCAB HV quartile (29-81/yr)	3rd OPCAB HV quartile (82-163/yr)	4th OPCAB HV quartile (≥164/yr)
OPCAB(n)		546,243	48,120	107,202	145,026	245,895
nONCAB(n)		1,547,851	488,261	410,176	380,913	268,502
Mortality (%)						
OPCAB		2.5%	3.5%	3.0%	2.7%	2.1%
ONCAB		2.0%	1.9%	1.9%	2.0%	2.2%
$\varkappa^2$ *P-value*		<0.0001	<0.0001	<0.0001	<0.0001	0.73
Hospital stay (days)						
OPCAB		9.6±0.13	10.9±0.17	10.3±0.16	9.6±0.15	9.2±0.24
ONCAB		9.2±0.07	9.2±0.09	9.1±0.11	9.2±0.15	9.3±0.21
$\varkappa^2$ *P-value*		0.0003	<0.0001	<0.0001	0.16	0.78
Total costs ($)						
OPCAB		115,019±3,613	146,499±3,994	127,551±3980	112,495±4136	104,878±6,916
ONCAB		110,721±2,326	124,110±3,843	108,852±4653	99,960±4052	103,547±5,869
$\varkappa^2$ *P-value*		0.20	<0.0001	<0.0001	0.0004	0.81

OPCAB: off-pump coronary artery bypass grafting; ONCAB: on-pump coronary artery bypass grafting.

Table 3. Risk-adjusted estimates for ONCAB versus OPCAB on outcomes according to OPCAB hospital volume (P<.05 in bold)

		Overall	1st OPCAB HV quartile (<29/yr)	2nd OPCAB HV quartile (29-81/yr)	3rd OPCAB HV quartile (82-163/yr)	4th OPCAB HV quartile (≥164/yr)
OPCAB(n)		546,243	48,120	107,202	145,026	245,895
ONCAB(n)		1,547,851	488,261	410,176	380,913	268,502
Mortality (%)						
	model 1	1.04 [0.94-1.14]	**1.30 [1.11-1.51]**	1.16 [0.99-1.37]	1.07 [0.93- 1.24]	**0.81 [0.65-0.99]**
	model 2	1.02 [0.93-1.12]	**1.29 [1.10-1.50]**	1.11 [0.95-1.30]	1.02 [0.88- 1.18]	**0.80 [0.65-0.98]**
Hospital stay (days)						
	model 1	0.19±0.12	**1.09±0.16**	**0.57±0.15**	0.05±0.13	0.05±0.23
	model 2	0.19±0.12	**1.03±0.16**	**0.76±0.15**	0.19± 0.12	0.20±0.23
Total costs ($)						
	model 1	2063±3730	**15,905±3824**	**12,848±4651**	**13,390±3313**	2387±6258
	model 2	-944±3659	**11,823±3159**	5630±3501	4025±2556	-4351±4598

OPCAB: off-pump coronary artery bypass grafting; ONCAB: on-pump coronary artery bypass grafting

model 1: clustered for ID Hospital + patient level variables including age, gender, race, elective admission and risk related to coexisting medical conditions + hospital-level variables such as hospital region, location teaching status, and bed size; model 2: model 1 + ONCAB hospital volume + year of surgery

Table 4. Risk-adjusted estimates for OPCAB versus ONCAB on outcomes according to OPCAB surgeon volume (P<.05 in bold)

		Overall	1st OPCAB SV quartile (<6/yr)	2nd OPCAB SV quartile (6-18/yr)	3rd OPCAB SV quartile (19-47/yr)	4th OPCAB SV quartile (≥48yr)
OPCAB		295,045	31,065	39,037	65,624	159,319
ONCAB		729,827	241,540	206,588	187,573	94,126
Mortality (%)						
	model 1	1.03 [0.90-1.17]	**1.28 [1.08- 1.53]**	**1.30 [1.08-1.56]**	**1.28 [1.08-1.51]**	**0.64 [0.51-0.80]**
	model 2	0.99 [0.87-1.12]	**1.23 [1.02-1.48]**	**1.30 [1.08-1.58]**	**1.26 [1.05-1.50]**	**0.58 [0.45-0.71]**
Hospital stay (days)						
	model 1	**0.36±0.18**	**2.12±0.22**	**1.30±0.20**	**0.60±0.22**	-0.16±0.22
	model 2	0.31±0.17	**1.76±0.21**	**1.37±0.20**	**0.73±0.22**	-0.15±0.17
Total costs ($)						
	model 1	5,534±4,597	**28,480±4653**	**18,258±3803**	**13,028±3623**	-9109±5229
	model 2	1438±4463	**20,773±4264**	**13,096±2902**	5,886±3139	**-10,778±4172**

OPCAB: off-pump coronary artery bypass grafting; ONCAB: on-pump coronary artery bypass grafting

model 1: clustered for ID Hospital + patient level variables including age, gender, race, elective admission and risk related to coexisting medical conditions + hospital-level variables such as hospital region, location teaching status, and bed size; model 2: model 1 + ON-CABG hospital volume + year of surgery

Table 5. Subgroup analyisis (hospital and surgeon volume) on primary outcome (in-hospital mortality) according to number of grafts performed (1 vesus ≥2 grafts) (P<.05 in bold)

Analysis according to Hospital Volume	Overall	1st OPCAB HV quartile (<29/yr)	2nd OPCAB HV quartile (29-81/yr)	3rd OPCAB HV quartile (82-163/yr)	4th OPCAB HV quartile (≥164/yr)
1 grafts					
OPCAB(n)	112,587	10,861	22,852	31,032	47,843
ONCAB(n)	200,064	61,486	53,882	51,287	33,410
Model 2	**0.82 [0.71-0.96]**	1.06 [0.75-1.49]	0.98 [0.71- 1.36]	**0.70 [0.52- 0.96]**	**0.66 [0.49-0.89]**
≥2 grafts					
OPCAB(n)	433,655	37,259	84,350	113,994	198,052
ONCAB(n)	1,347,787	426,775	356,294	329,626	235,092
Model 2	1.06 [0.96-1.17]	**1.32 [1.06-1.57]**	1.13 [0.97-1.31]	1.09 [0.93-1.26]	**0.82 [0.66- 0.99]**
Analysis according to Surgeon Volume	Overall	1st OFF-CABG SV quartile (<6/yr)	2nd OFF-CABG SV quartile (6-18/yr)	3rd OFF-CABG SV quartile (19-47/yr)	4th OFF-CABG SV quartile (≥48yr)
1 graft					
OPCAB (n)	60,702	6,566	9,338	14,315	30,483
ONCAB (n)	94,397	33,170	27,183	23,148	10,897
Model 2	0.85 [0.69-1.05]	1.06 [0.69-1.62]	1.31 [0.86-1.99]	**1.64 [1.06- 2.53]**	**0.33 [0.22- 0.47]**
≥2 grafts					
OPCAB (n)	234,344	24,500	29,700	51,309	128,836
ONCAB (n)	635,429	208,370	179,405	164,425	83,229
Model 2	1.007 [0.88-1.15]	**1.26 [1.03-1.53]**	**1.26 [1.02-1.56]**	1.21 [0.99-1.47]	**0.63 [0.49- 0.81]**

OPCAB: off-pump coronary artery bypass grafting; ONCAB: on-pump coronary artery bypass grafting

Clustered for hospital ID and adjusted for patient level variables including age, gender, race, elective admission and risk related to coexisting medical conditions and hospital-level variables such as hospital region, location teaching status, and bed size.

Supplementary Figure 1. Total number of OPCAB(red) and ONCAB(blue) procedures performed during the study period .

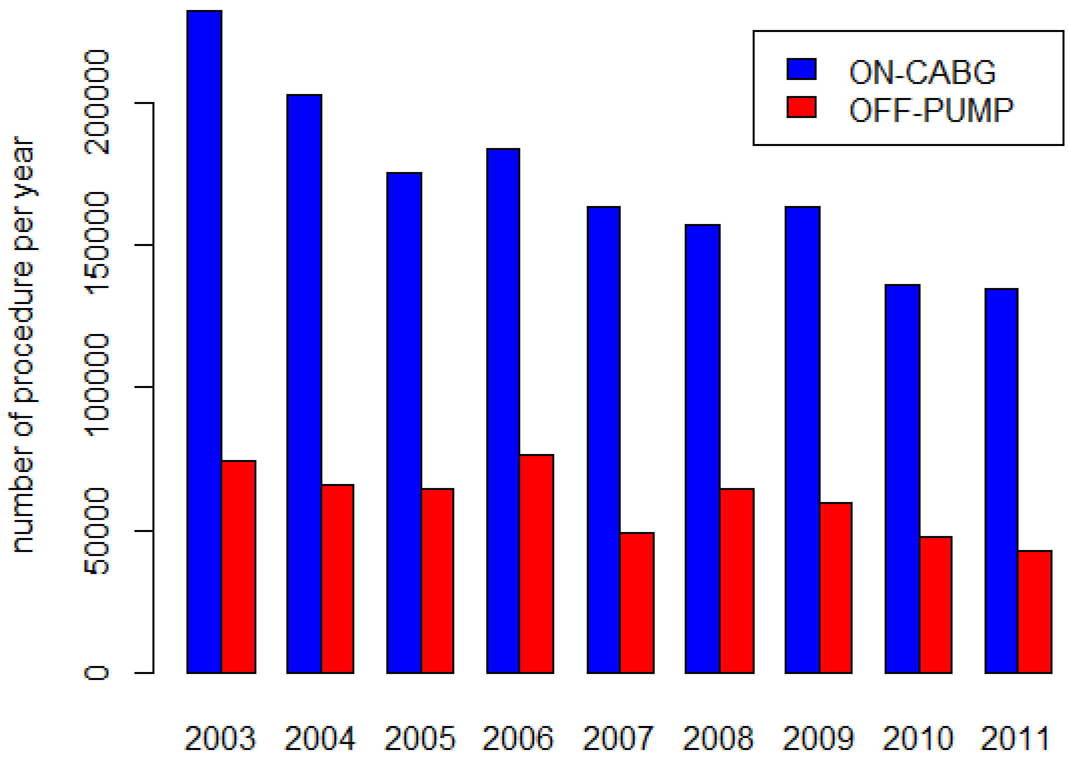

Figure 2. Number of OPCAB (red) and ONCAB (blue) procedures per centre (horizontals) ordered for OPCAB hospital volume (top) and OPCAB rate per centre (horizontals) ordered for total hospital volume (bottom)